# Quantum Electronic Solids

**Integrity ★ Service ★ Excellence**

**07 March 2012**

**Dr. Harold Weinstock**
**Program Manager**
**AFOSR/RSE**
**Air Force Research Laboratory**

# Report Documentation Page

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# QUANTUM ELECTRONIC SOLIDS

**NAME: Dr. Harold Weinstock**

**BRIEF DESCRIPTION OF PORTFOLIO**

**Physics and electronics at the nanoscale: superconductivity, metamaterials and nanoelectronics - exploiting quantum phenomena to create faster, smarter, smaller and more energy efficient devices**

**SUB-AREAS IN PORTFOLIO**

**Superconductivity: find new, more useful materials for high magnetic fields, microwave electronics, power reduction and distribution**

**Metamaterials: microwave, IR & optical sensing and signal processing with smaller sizes and unique properties**

**Nanoelectronics: NTs, graphene, diamond, SiC for sensing, logic & memory storage**

# Seekers of New Superconductors

**MURI**: 1. Stanford, Princeton, Rice, Rutgers (Beasley)

2. UCSD, UCI, UW-Milw, Complutense (Schuller)

3. Maryland, Iowa State, UCSD (R. Greene)

**Plus**: 1. Houston, TAMU, Academia Sinica Taiwan (Chu)

2. UT-Dallas, Clemson, Aoyama Gakuin (Zakhidov)

3. Stony Brook, UCSD, Rutgers, (Aronson, Basov, Kotliar)

4. Florida International (Larkins, Vlasov)

5. Brookhaven, Stanford (Bozovic, Geballe)

6. Tel Aviv, Stanford, Twente (Deutscher, Geballe, Koster)

7. PECASE: TAMU, Rice, Cornell (Wang, Morosan, Shen)

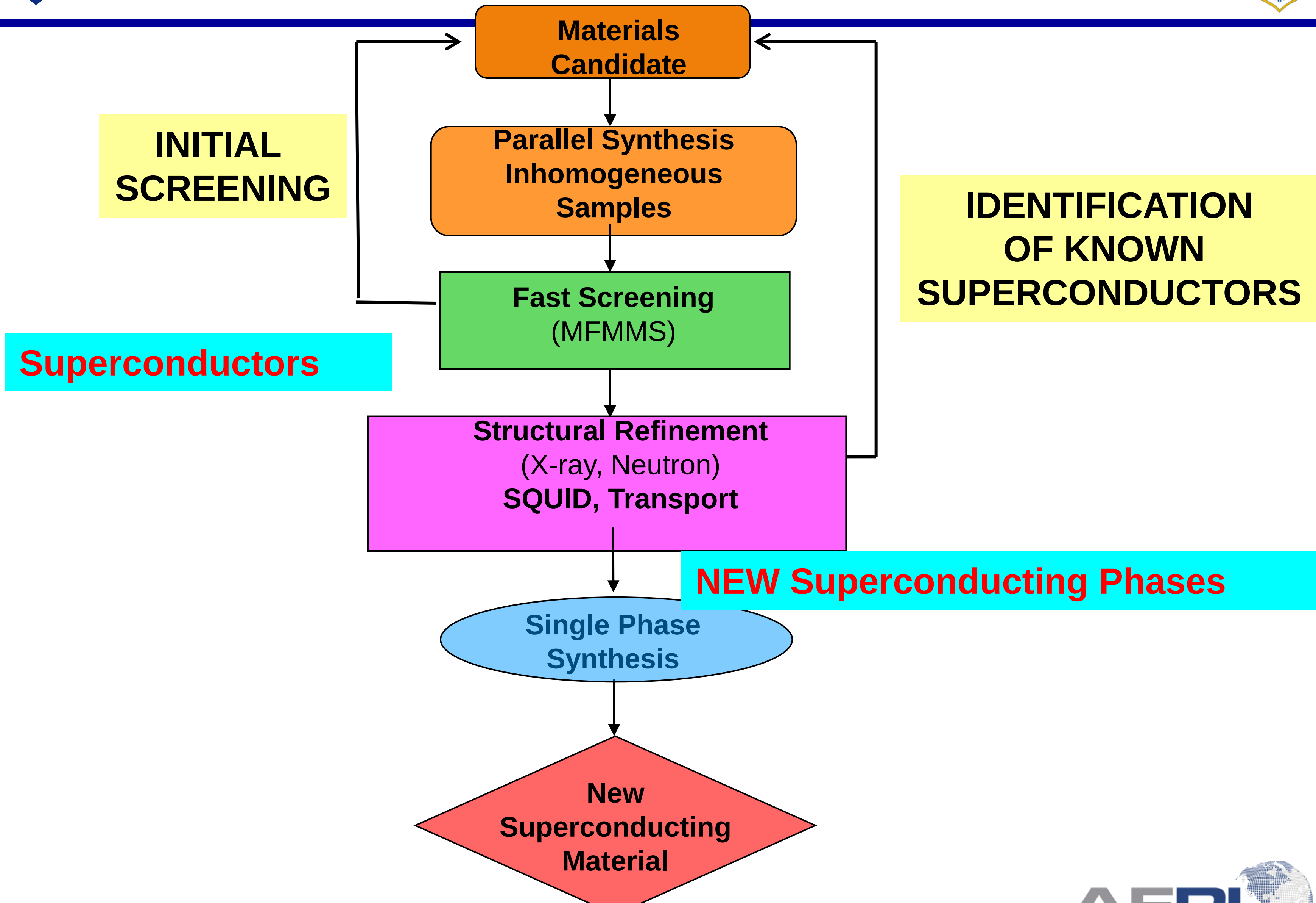
8. AFRL/RZPG (Tim Haugan)

9. IoP of CAS + Chinese universities (Zhao et al.)

# Guidance for New Superconductors

- **To obtain $T_c$ = 300K, not of great concern whether it is a 2D or 3D superconductor, but for most applications desire 3D.**
- **Alternately, could be either s-wave or d-wave pairing of electrons in achieving $T_c$ = 300K, but for applications prefer s-wave pairing.**
- **No known reason why the el-ph interaction can't work well at 300 K.**
- **Hope for large density of states, especially for applications.**

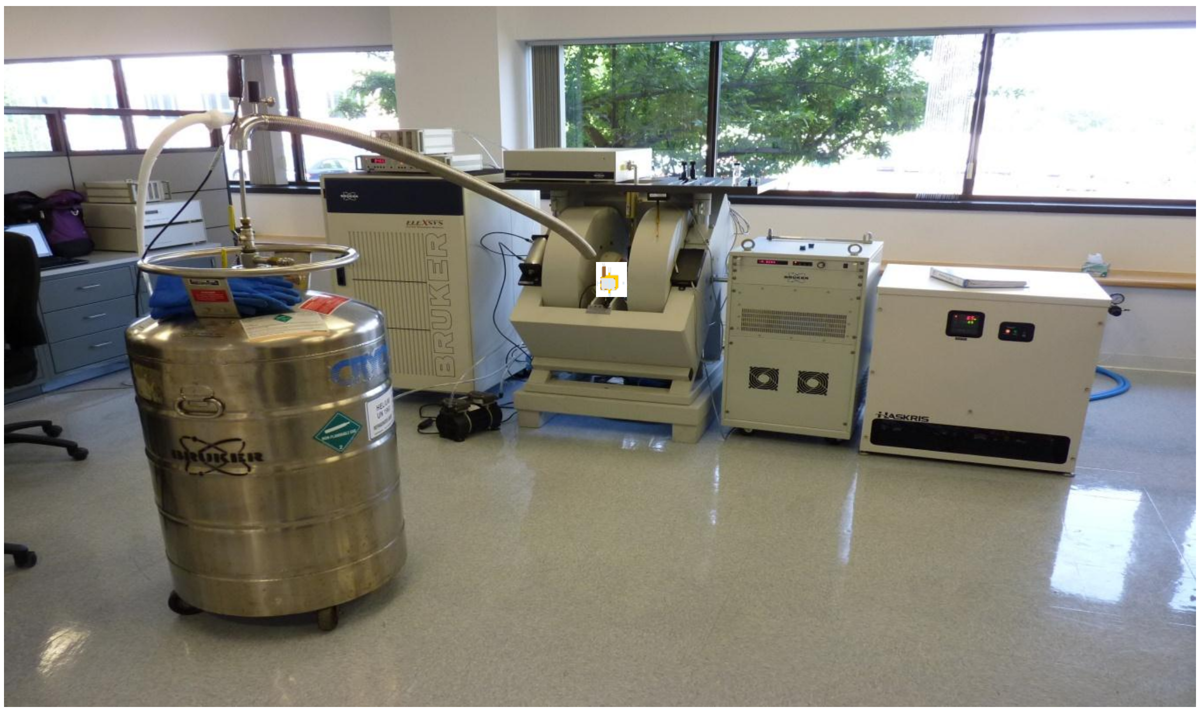
# Supersearch Methodology
# Ivan Schuller - UCSD

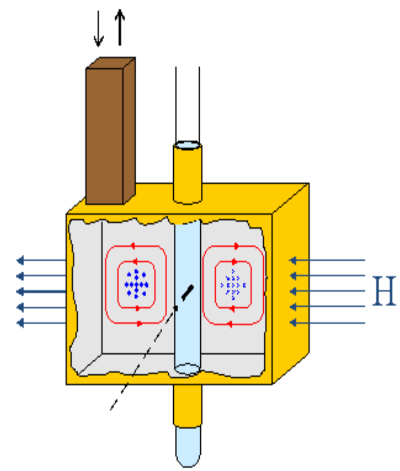


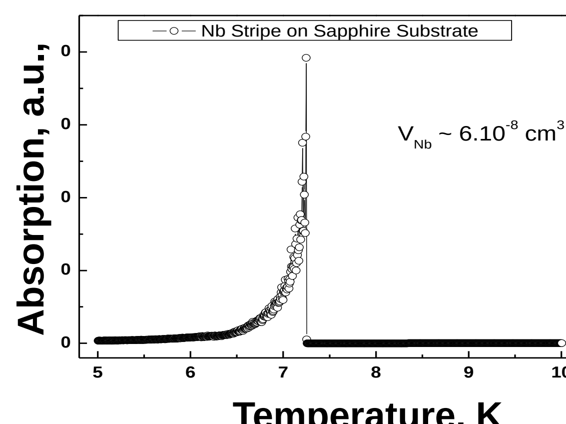
# Sensitive & Selective

## Mag. Field Modulated Microwave Spectroscopy

### Oscillate H field, scan T, detect absorption




**Detection limit $5 \times 10^{-12}$ cm$^3$**

# Results

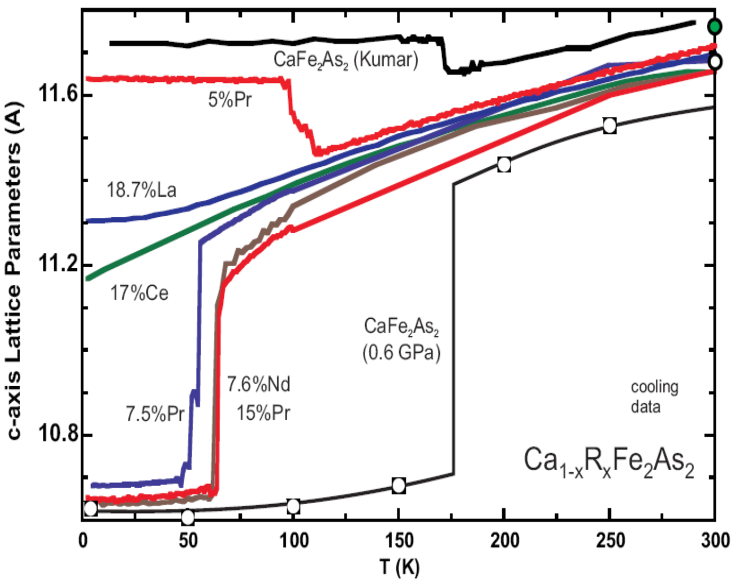
## Ivan Schuller – UCSD

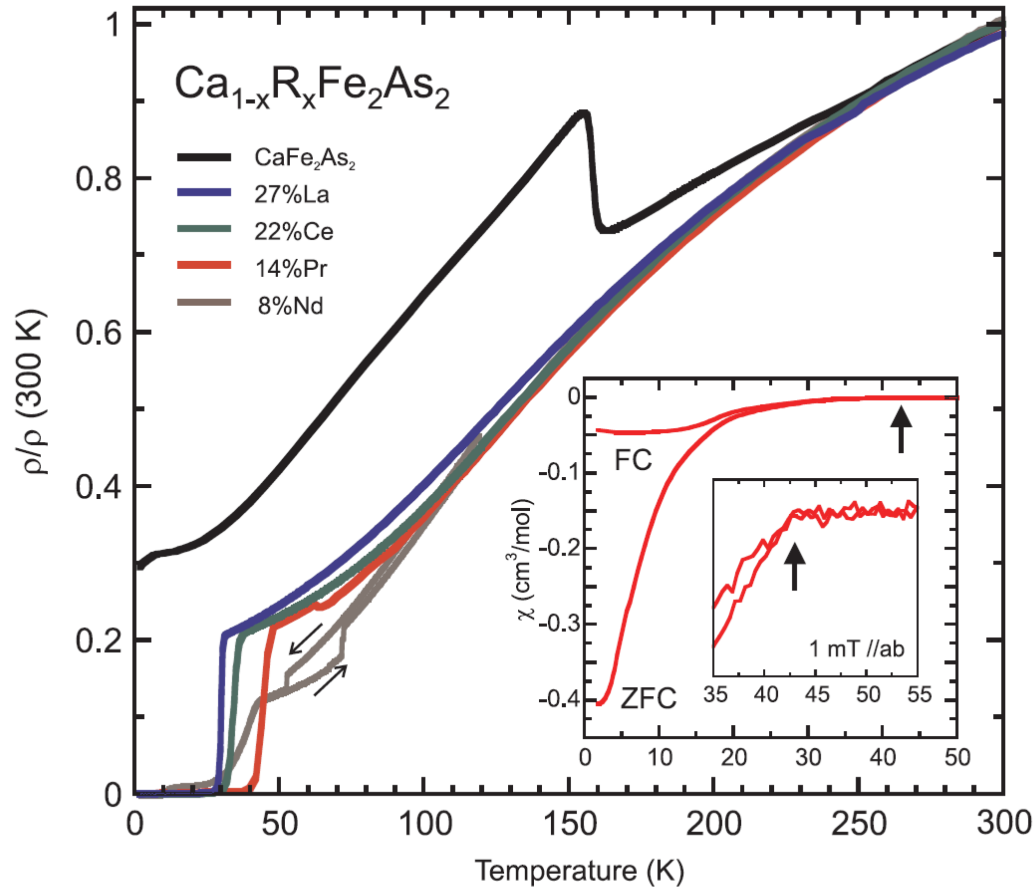
- **SYSTEMATIC studies**
  1. $RE_5Si_3$+dopants
     - $Pr_5Si_3$ +C, 85K Ferromagnet
     - $Eu_5Si_3$ 27K Superconductor ?
     - YBCO preformed superconducting pairs at 180K
  2. $AlB_2$-high pressure synthesis Tc~ 7K ?
  3. $Th_5Ni_4C$- Tc~5K
  4. CaCeIr- Tc~3K
  5. $ZrNb_xB$, ZrVxB- Tc~9K
  6. $ZrV_xS_2$, $ZrV_xSe_2$, $ZrV_xTe_2$- Tc~7-9K
- **MFMMS - Open for business**
- **Collaborations-**
  **3 MURIs+Wen+Zhou+Risbud**
- **16 papers, 4 PhD theses,**
  **38 invited talks**

# Empirical Search for New SCs

## U Maryland-Iowa State-UC San Diego MURI (PI-R.L. Greene)

### *40+ K Superconductivity in rare earth-doped* $Ca_{1-x}R_xFe_2As_2$

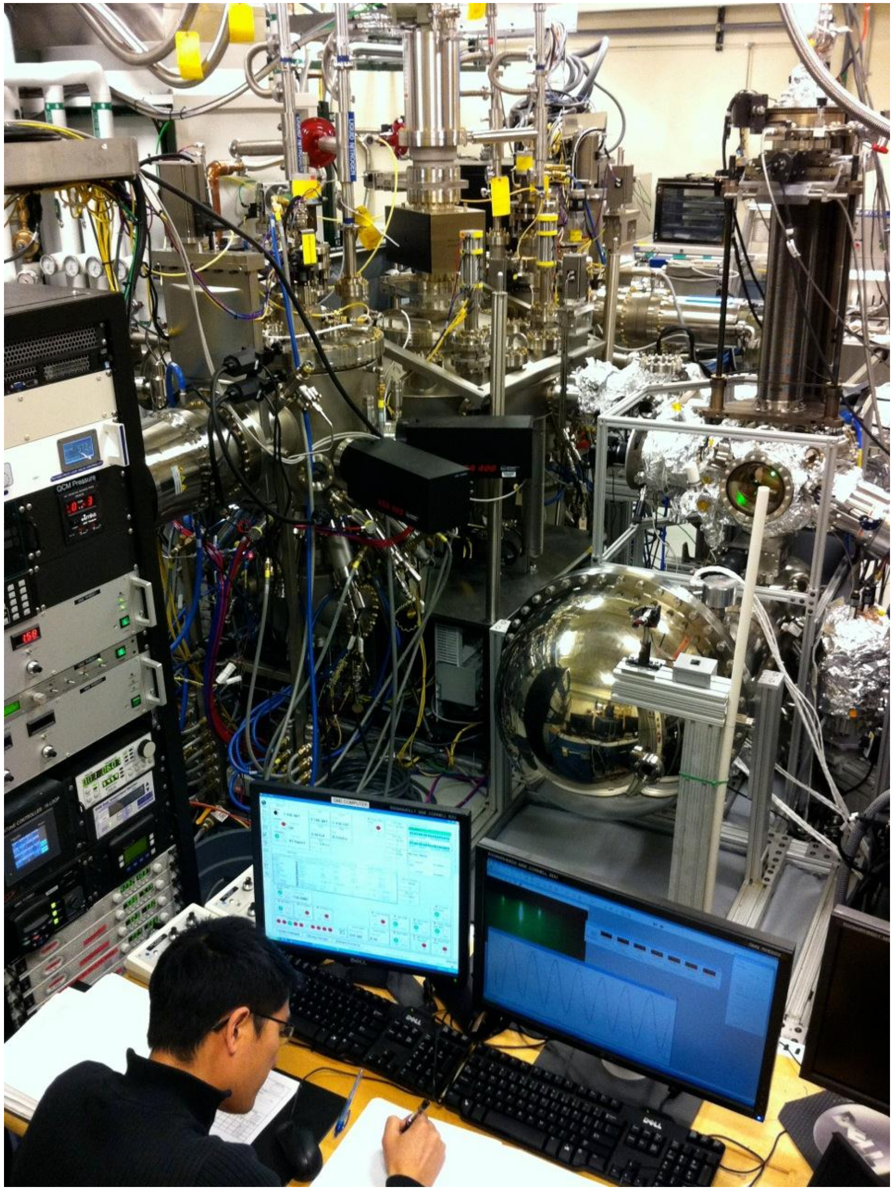



- **substitution-controlled lattice collapse**
- **high-Tc superconducting phase**

**S.R. Saha et al, arXiv: 1105.4798**

# Integrated MBE – ARPES
## Kyle Shen, Cornell U.

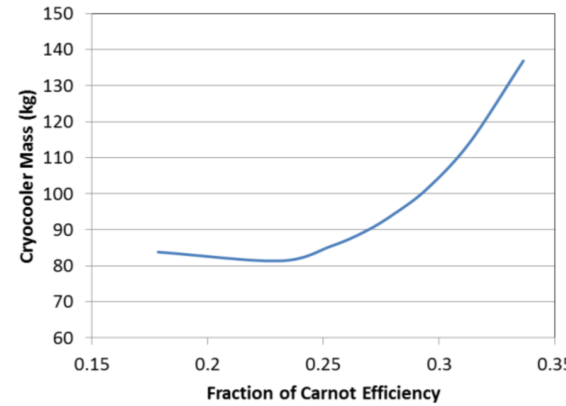


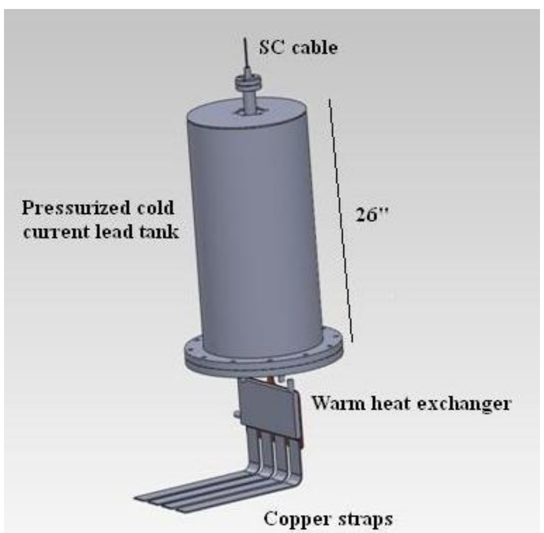
# SC Power Transmission for DE

A. Dietz, Creare Inc., L. Bromberg, MIT

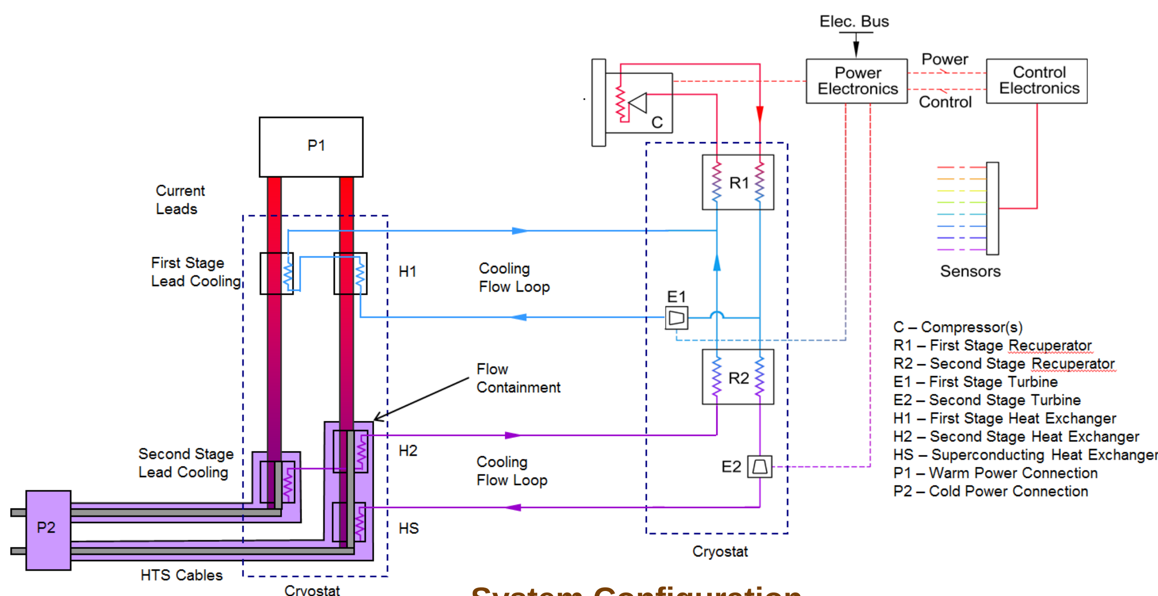
- Two-stage current leads with integrated heat exchangers cooled by cycle gas from a two-stage turbo-Brayton cryocooler
- Current lead design minimizes cold heat load and ensures even current distribution
- Cryocooler design offers high efficiency with low weight
- Advantages over copper cables
  - 90% less weight
  - 40% less power consumed

Cryocooler Performance



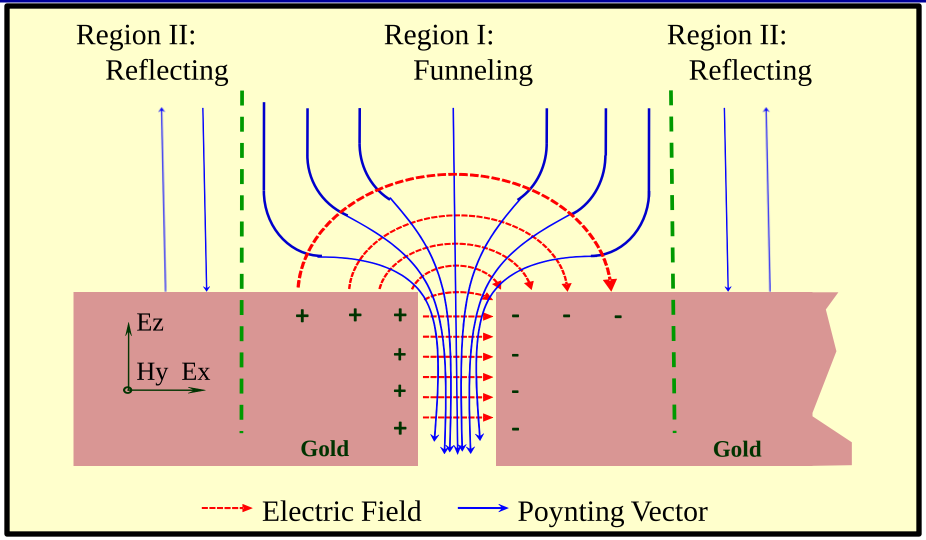

Current Lead Design

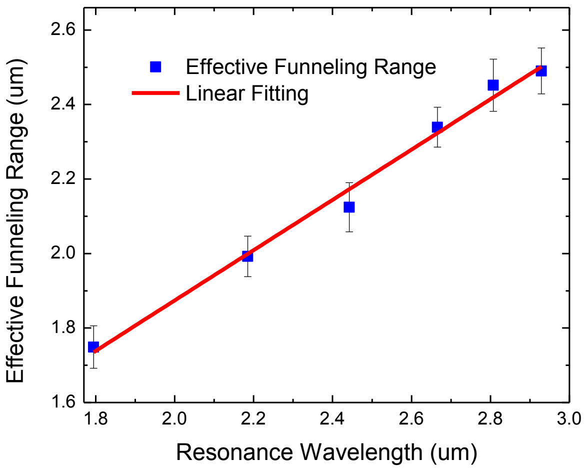



System Configuration

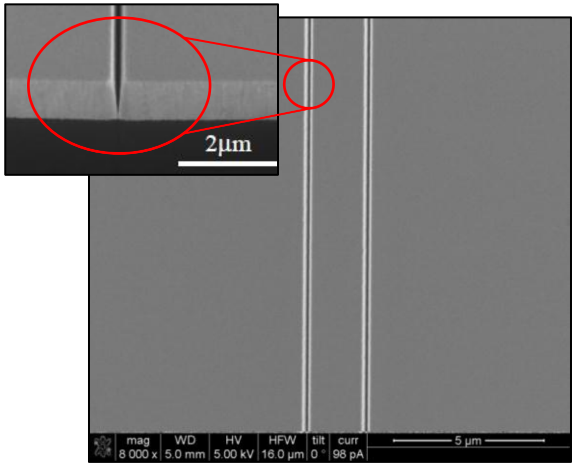
# Light Funneling into Deep Sub-λ Slits

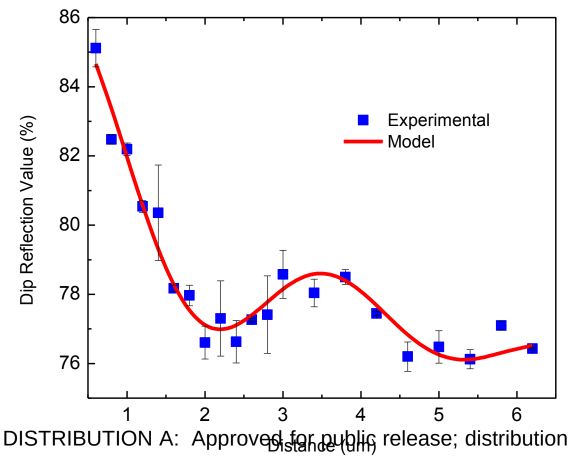
L. Jay Guo and R. Merlin, U. of Michigan

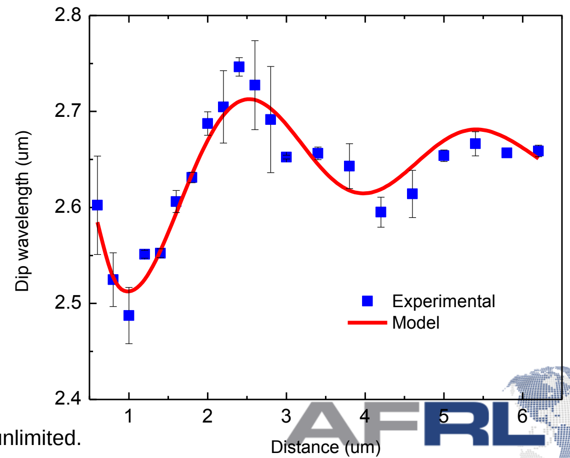



**Experimentally determined that light can be efficiently funneled into a nanoslit with an effective lateral range on the order of one wavelength. Effect can be explained in terms of electrostatic model. Also studied coupling effects for more than one slit.**



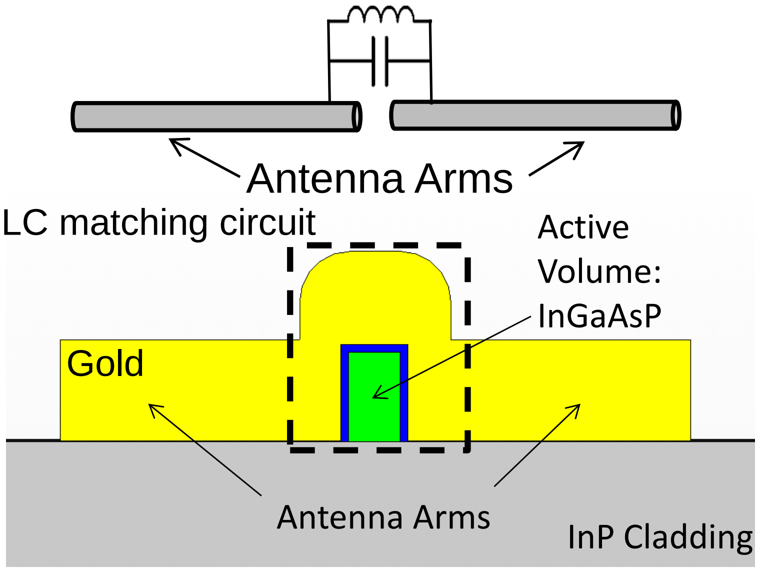



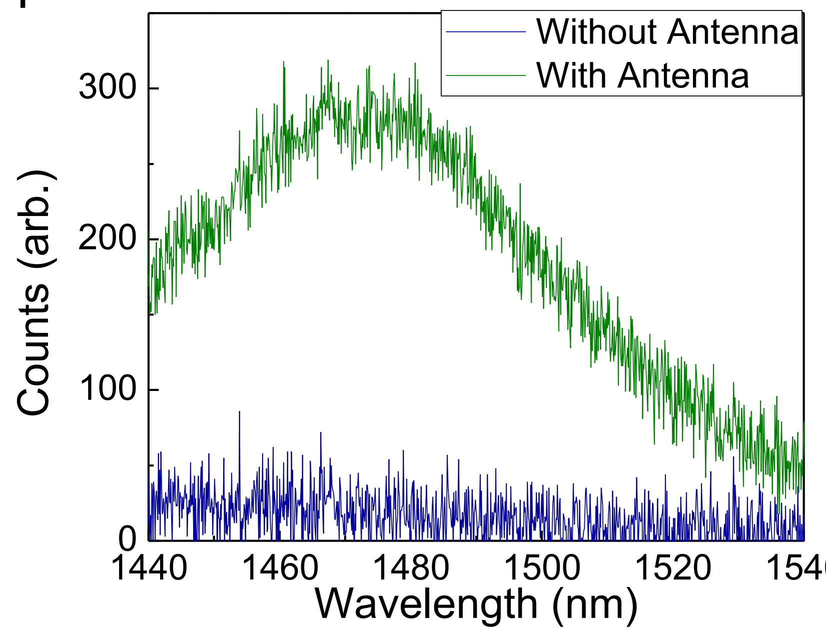
# Spontaneous Faster than Stimulated Emission

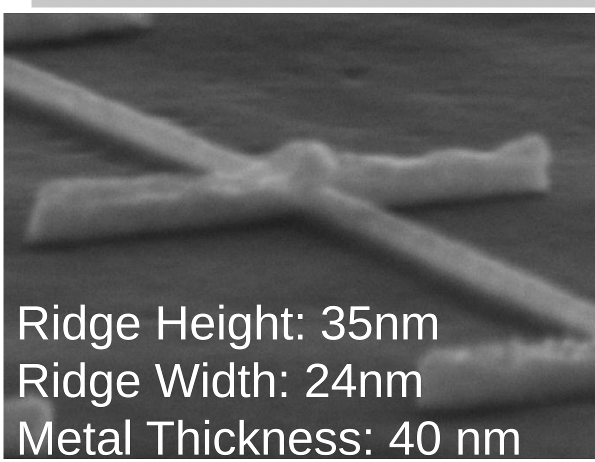
Eli Yablonovitch & Ming Wu, UC Berkeley

New Science: Changing the rules, spontaneous faster than stimulated!

New Technology: LED is faster than Laser!  BW of THz possible. Enables ultra-low power interconnects.




- **Optical-antenna-based nanoLED demoed.**

–Very small size. **0.015 $(\lambda/2n)^3$ Mode Volume**

–Spontaneous Emission Rate enhancement of **>8x**

–Semiconductor based - allow for high speed mod.

# Nonlinear Metamaterials

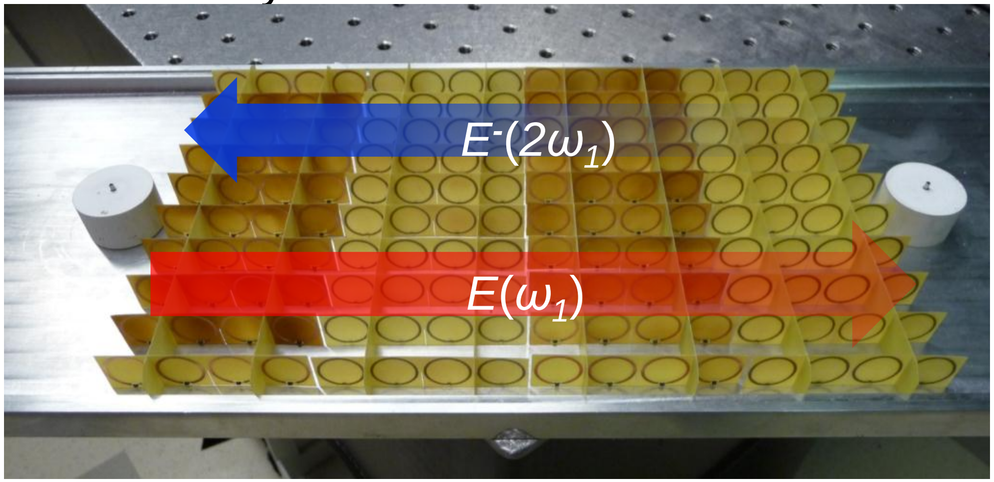
**D. R. Smith, Duke University**

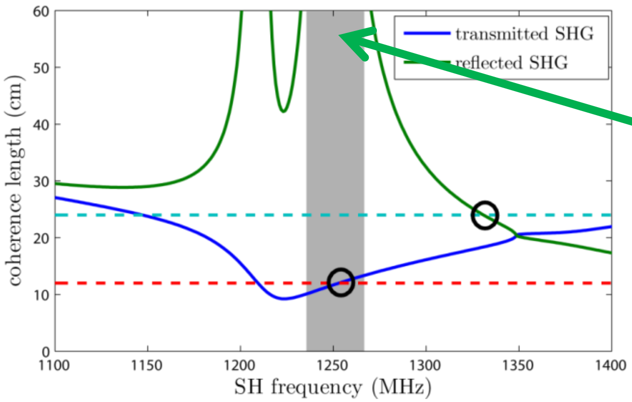
## Low Frequency Nonlinear MetaCrystals

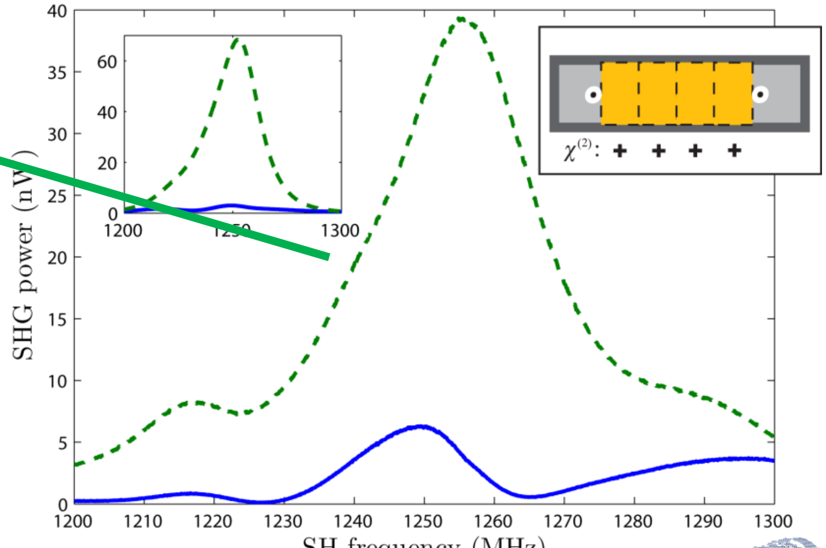
Nonlinear crystals play dominant role in optical systems as sources, wavelength shifters, amplifiers, etc.

Artificially-structured MetaCrystals can improve on nature.

MetaCrystal as “Nonlinear Mirror”




1st experimental demo of phase matching: neg. index nonlinear metacrystal produces 2nd harmonic reflected wave!

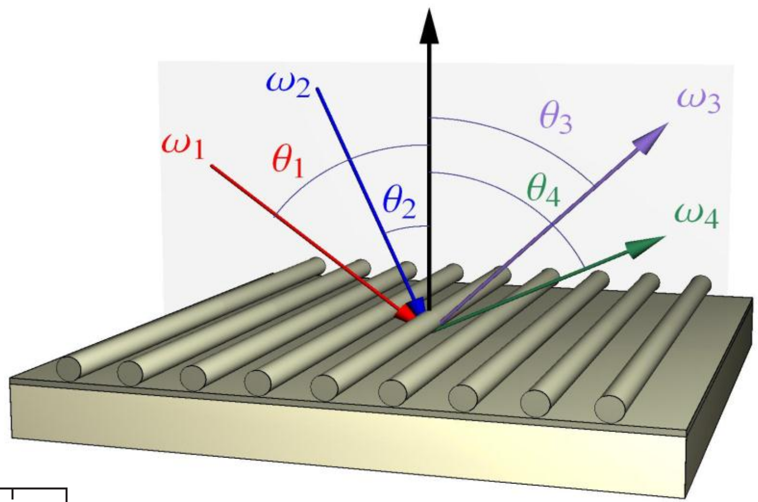
# Nonlinear Optical Metamaterials

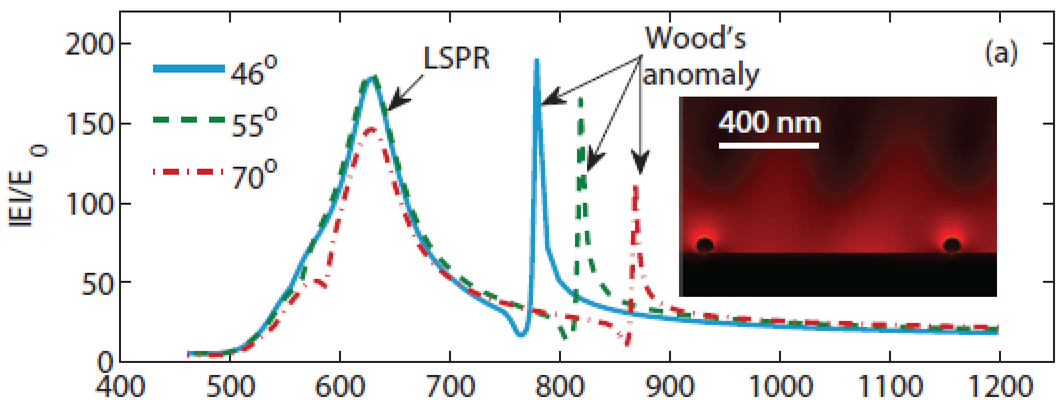
**D. R. Smith, Duke University**

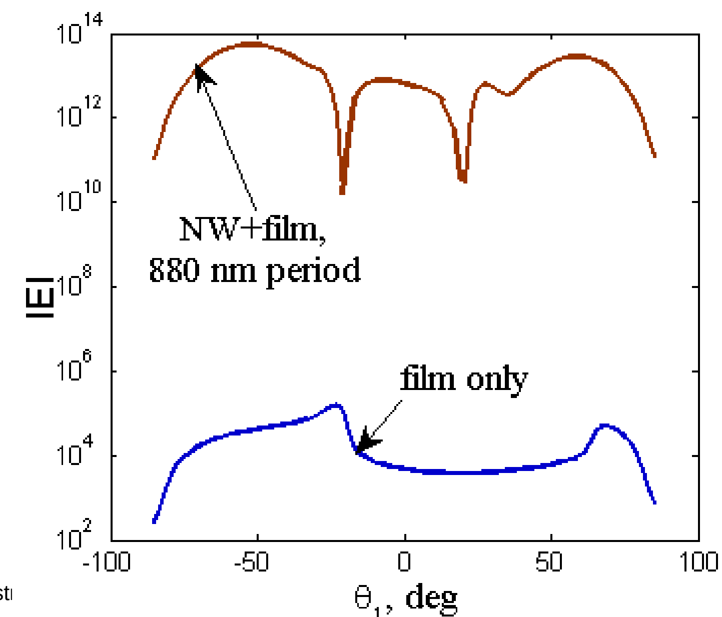
## Four wave mixing in an optical metacrystal

At IR and visible wavelengths, metals are extremely nonlinear and are a natural match for optical nonlinear metamaterials.

Field enhancement can play a critical role!



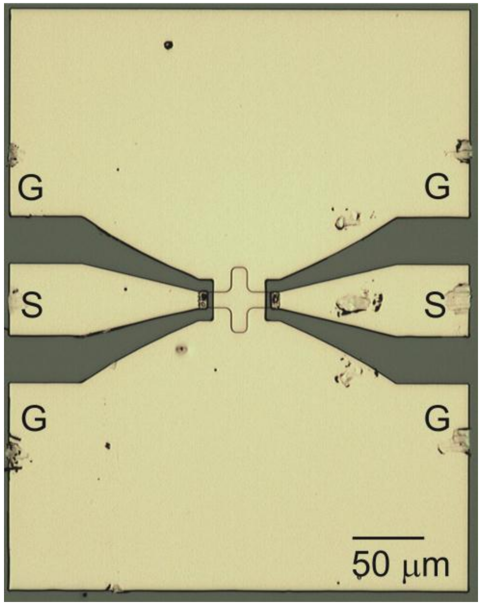



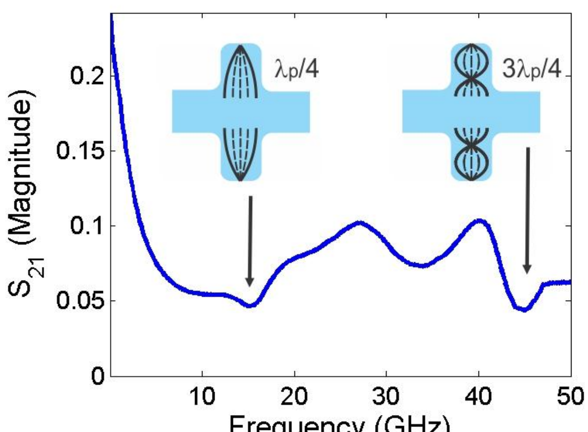

Simulation showing <u>huge enhancement of FWM light</u>, (>8 orders of mag.) using both localized & propagating surface plasmons!

# Ultra-Subwavelength 2D Plasmon Electronics

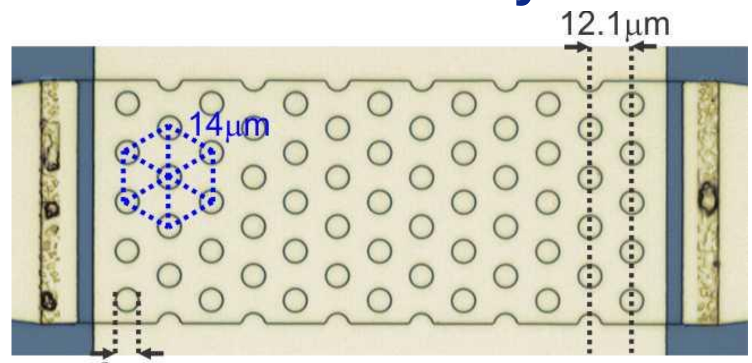
Donhee Ham, Harvard University

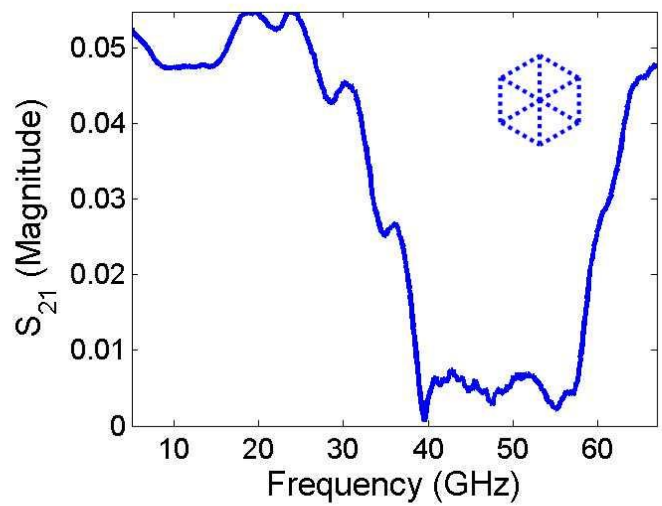
## 2D Plasmonic Nanoguide & Cavity




## 2D Plasmonic Crystal



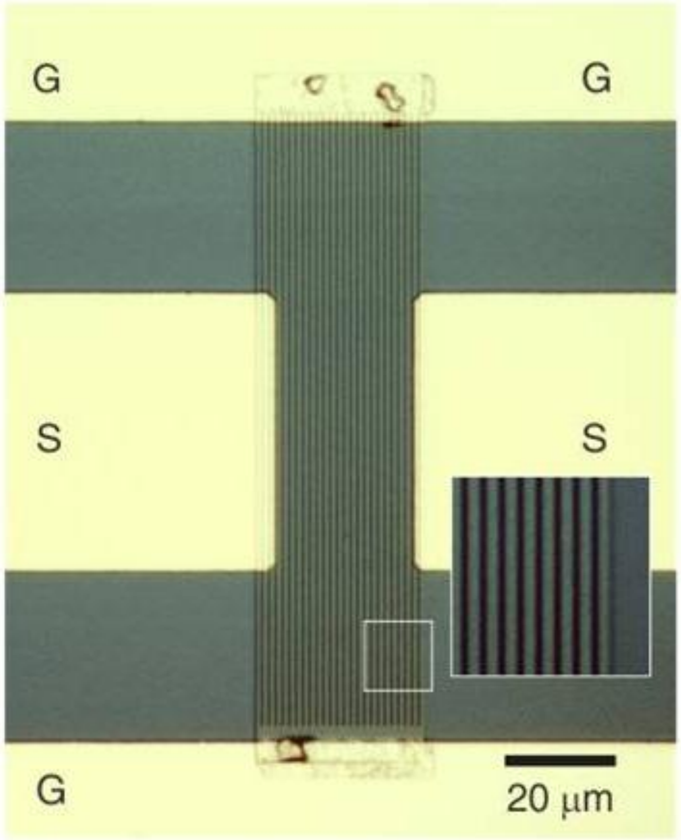




- $\lambda_p \sim \lambda/300$ (drastic subwavelength confinement)
- 2D plasmon manipulation to create circuits

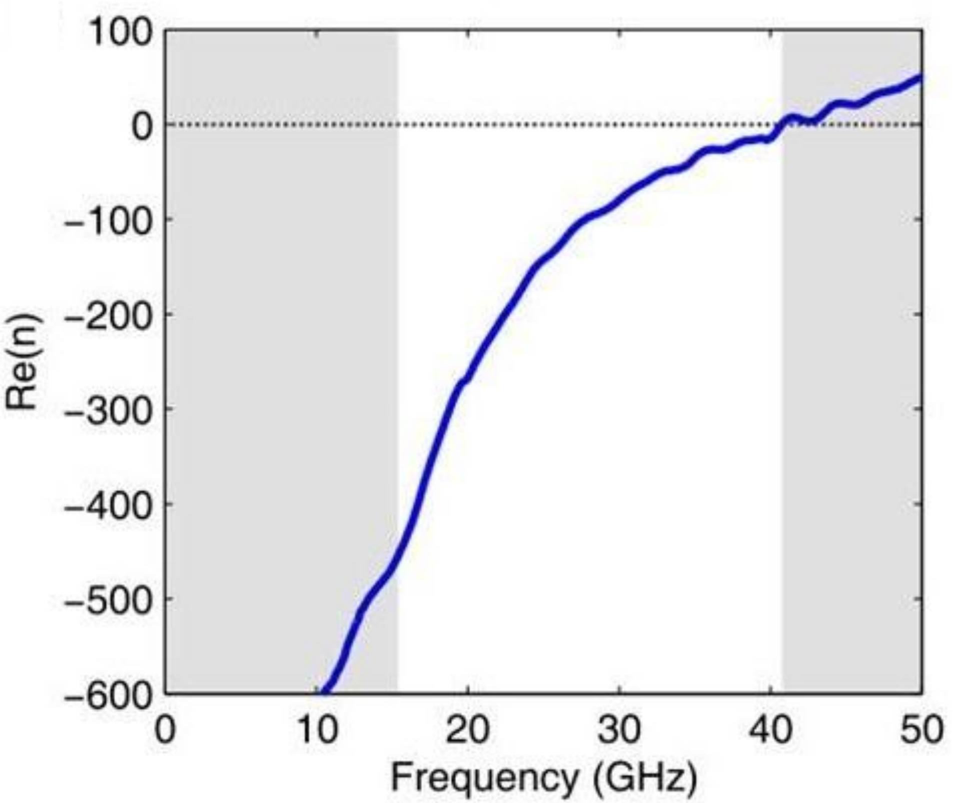
# Newtonian Route to Gigantic Neg. Refraction

**Donhee Ham, Harvard University**

2DEG electron-inertia-based negative index metamaterial




Gigantic negative index (up to -460)

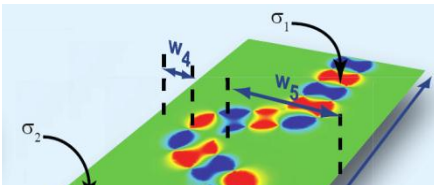


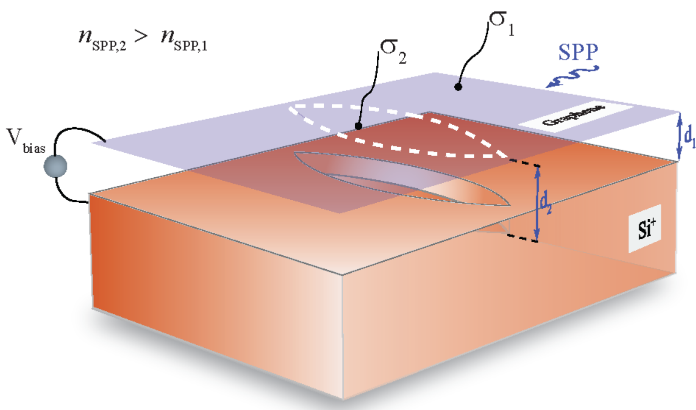

H. Yoon et al, *Nature* (under review)

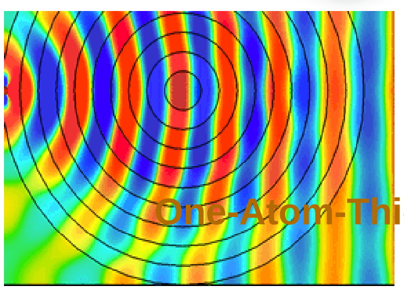
# MM-Inspired Optical Nanocircuits

Nader Engheta, U Penn

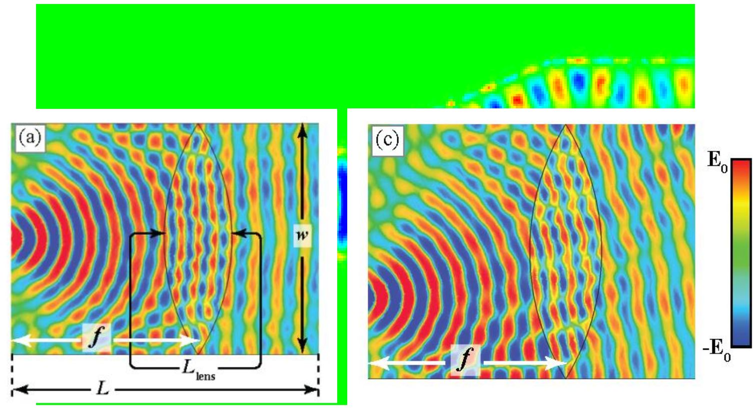
## Graphene Metamaterials, Graphene Metatronics, and Graphene Transformation Optics

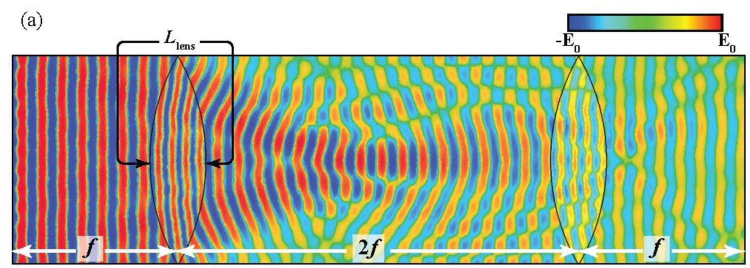


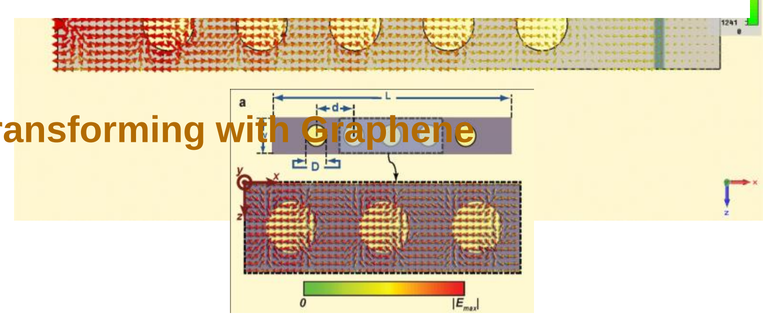



One-Atom-Thick Luneburg lens, as an example of Graphene Transformation Optics




One-Atom-Thick Optical Fourier Transforming with Graphene




One-Atom-Thick IR Metamaterials

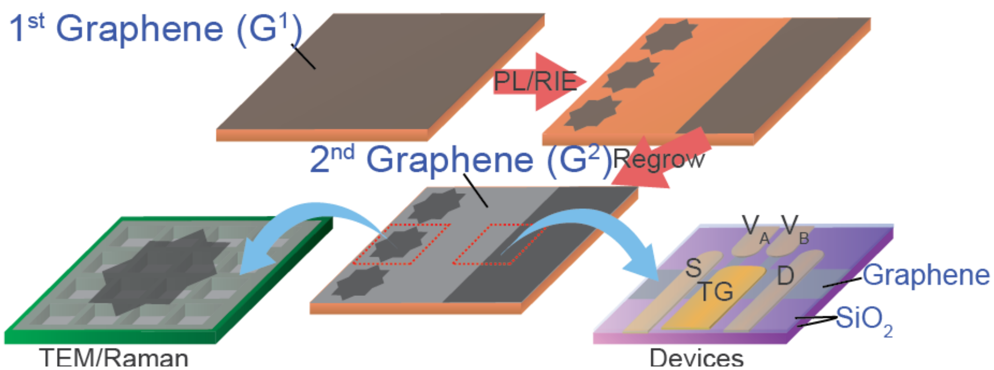


AFRL

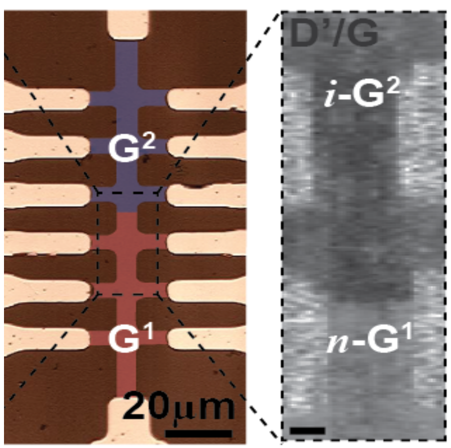
# Patterned Graphene Grows into Thin Heterojunctions
## Jiwoong Park, Cornell University

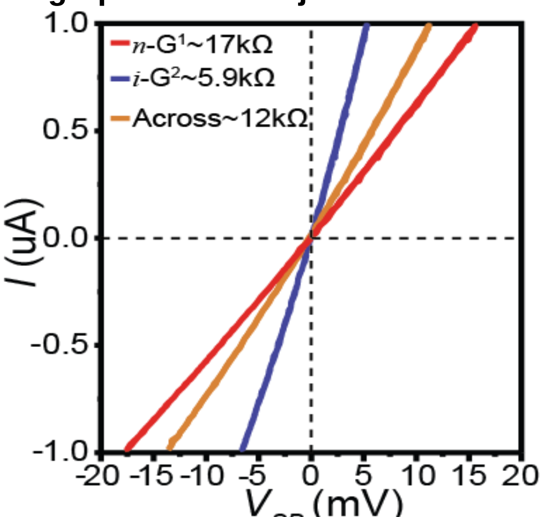
### New technique produces heterojunctions in single-atom-thick graphene

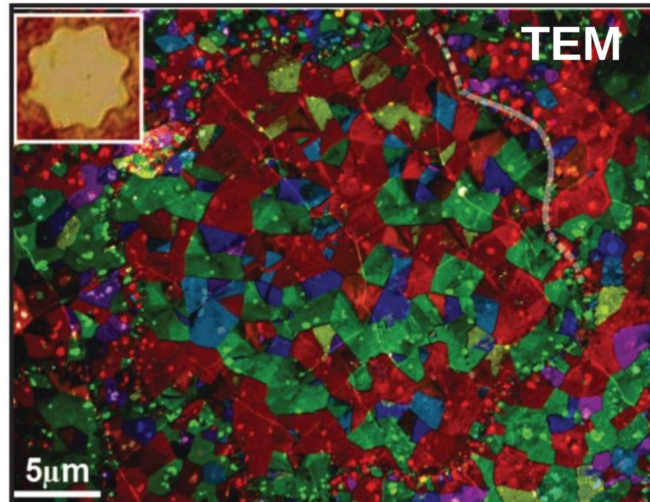
**Patterned regrowth process**

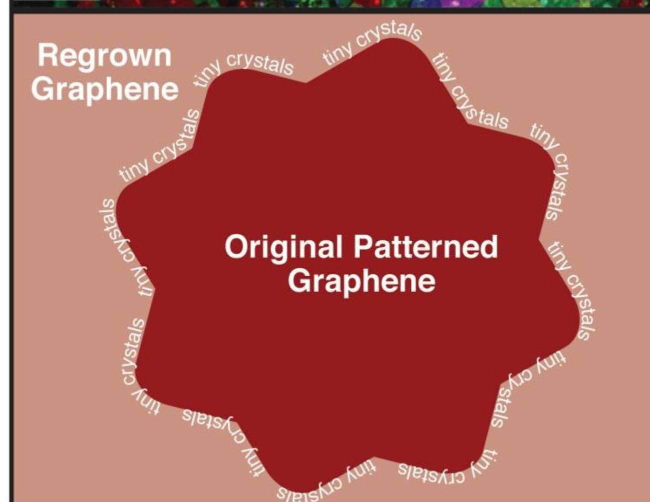



**Electrical continuity of synthesized *i-n* graphene heterojunctions**



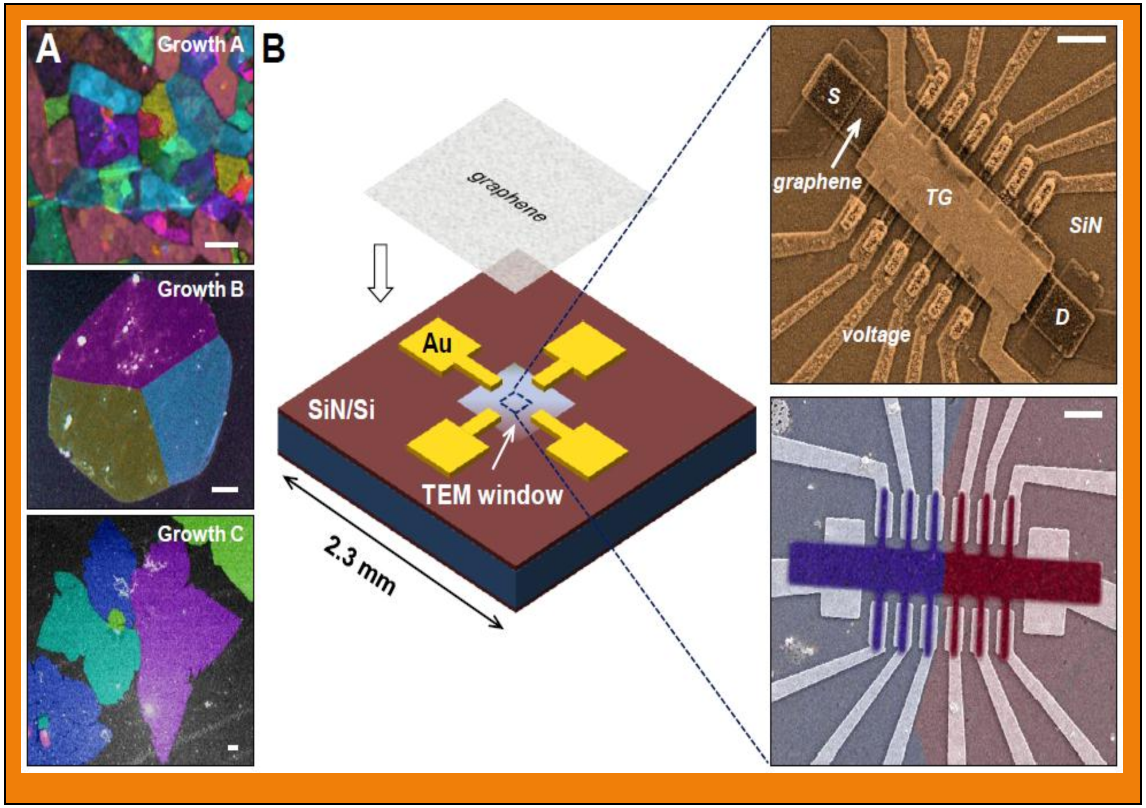


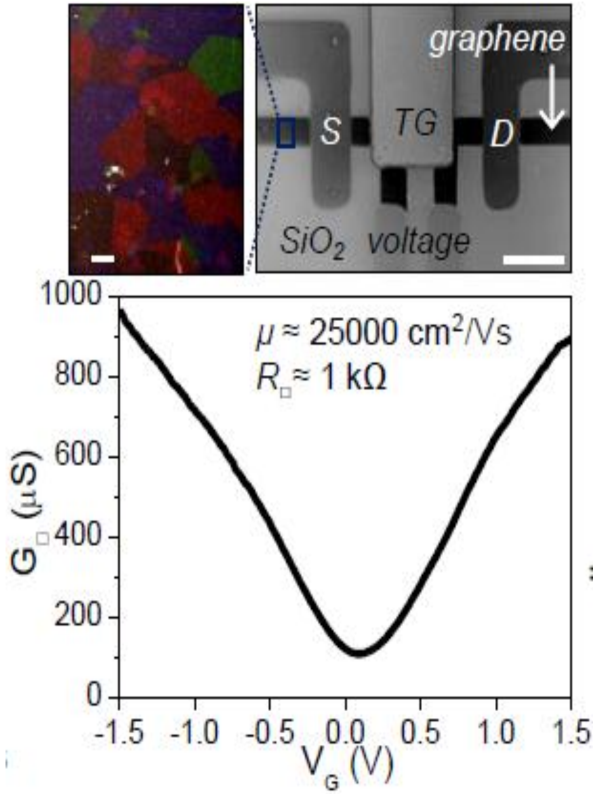
*M.P.Levendorf, et al. in preparation*

*FA9550-10-1-0410: LOW DIMENSIONAL CARBON MATERIALS FOR NANO-OPTICS AND NANOPLASMONICS*

# Electrical Properties of Polycrystalline Graphene
# Jiwoong Park, Cornell University

## Small-Grain Graphene shows excellent electrical performances



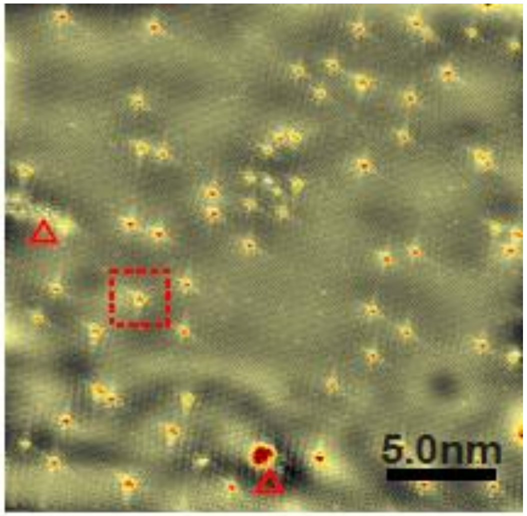

**High electrical conductance of grain boundaries in polycrystalline samples**

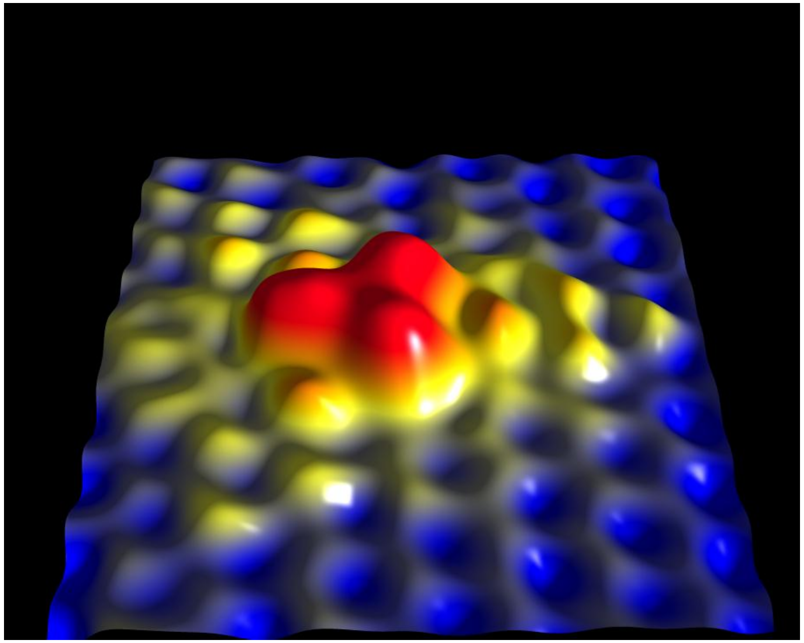
**Polycrystalline graphene can have similar (as much as 90%) electrical properties (conductance and mobility) as in single-crystalline exfoliated graphene.**

# Atomic Structure & Electronic Properties of Low-D Mat'ls

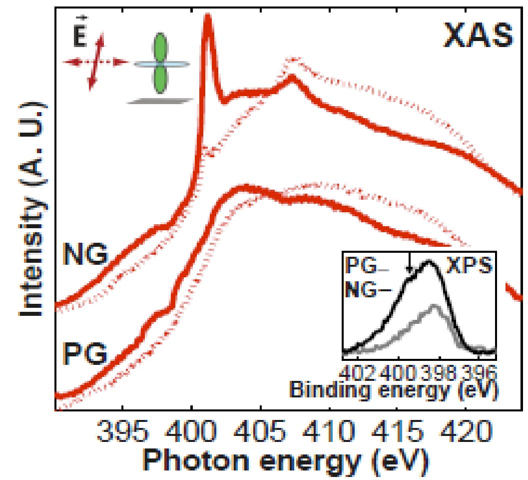
Abhay Pasupathy, Columbia University

## The local electronic structure of graphene doped with nitrogen



Above: *Left – Large area STM image of N dopants in a graphene monolayer and Right – atomic scale image of a single dopant showing the nitrogen dopant (red) in the graphene lattice (silver and blue)*



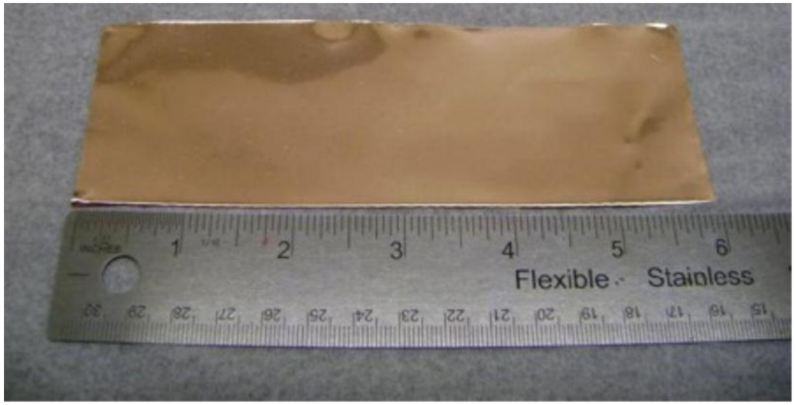

*Above: X-ray measurements of a nitrogen-doped graphene film (top) show a strong resonance due to graphitic nitrogen that is not present in pristine graphene (bottom)*

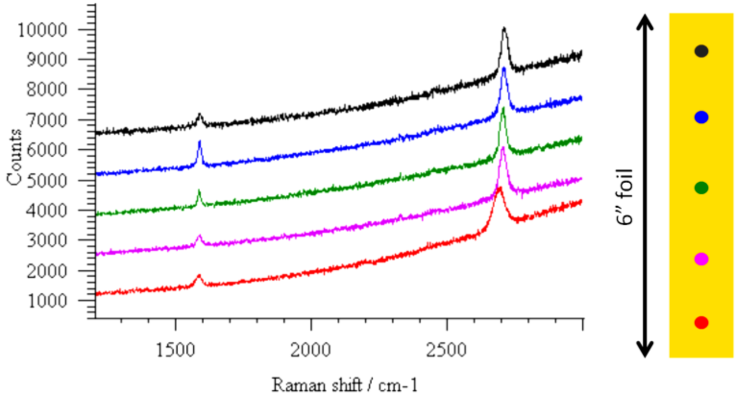
Published in: Zhao et al, *Science* **333**, 999 (2011)

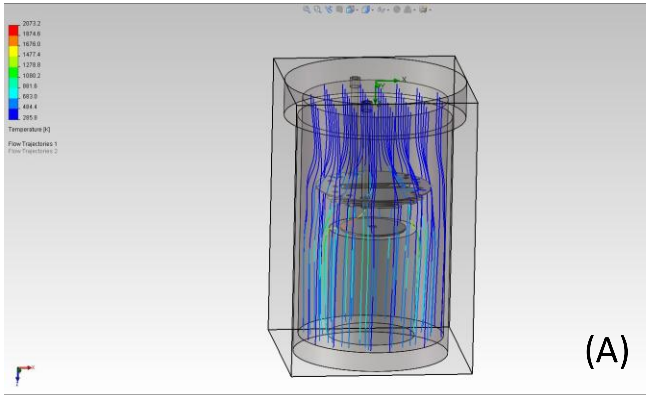
# Graphene Production Tool - STTR Phase II

**Structured Materials Industries: Nick Sbrockey, Bruce Willner, Gary Tompa**
**Cornell University: Jeonghyun Hwang, Michael Spencer**

Process development at Cornell and at SMI for graphene films by Si sublimation, and by CVD on metal and dielectric substrates.





Graphene film deposition tools are being designed, built and ***Sold*** by SMI.

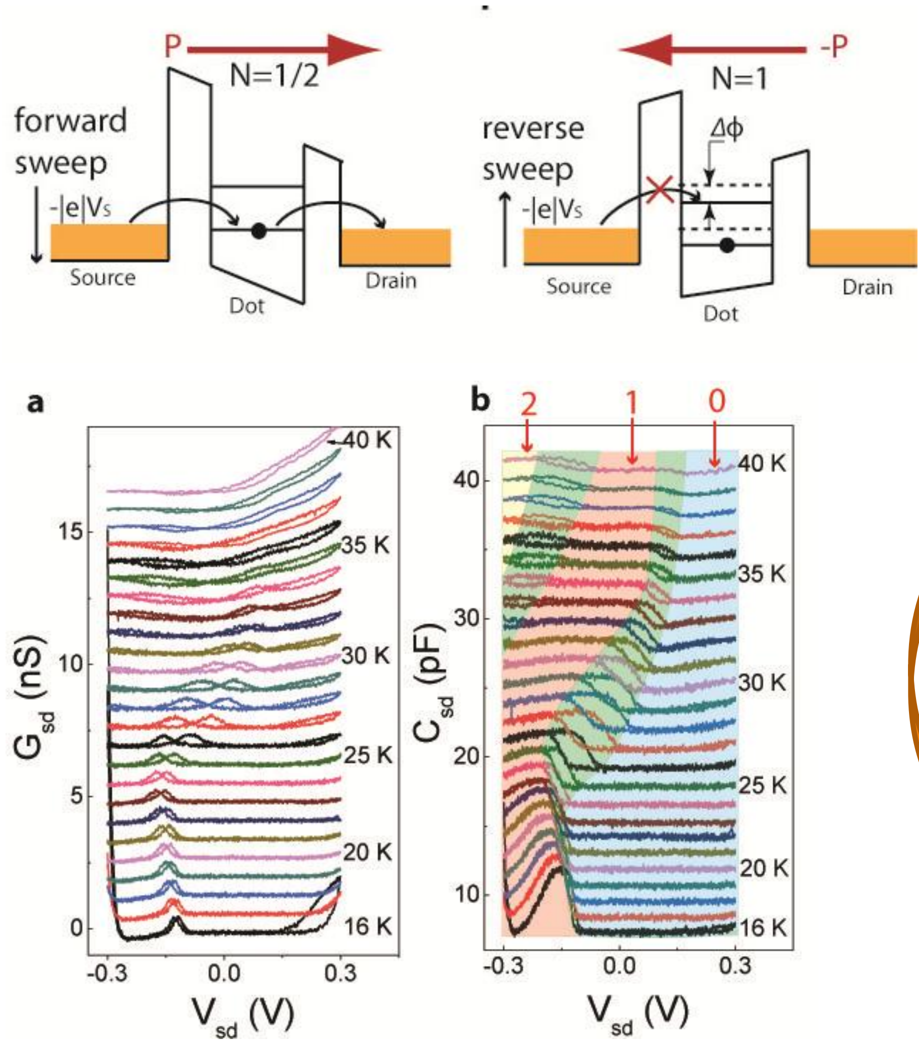
Cornell University

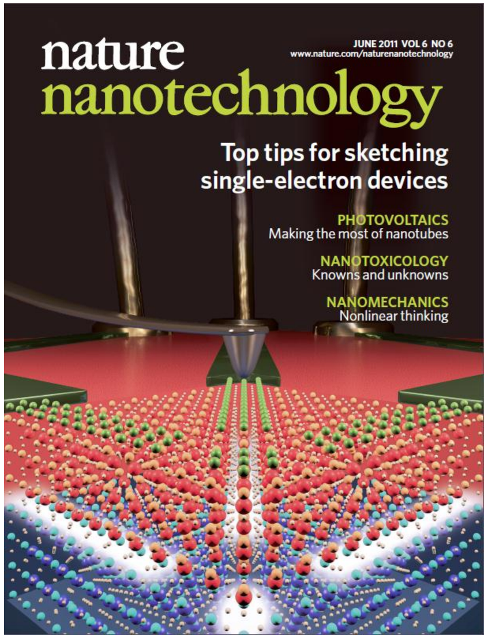


AFRL

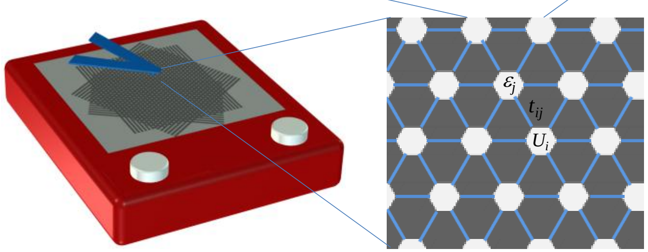
# Sketched Oxide Single-Electron Transistor

## FY10 SuperSemi MURI – J. Levy, U. of Pittsburgh




$$H = \sum_{i,\sigma} \varepsilon_i n_{i\sigma} - \sum_{<ij>,\sigma} t_{ij}\left(c^{\dagger}_{i\sigma} c_{j\sigma} + h.c.\right) + \sum_{i} U_i n_{i\uparrow} n_{i\downarrow}$$

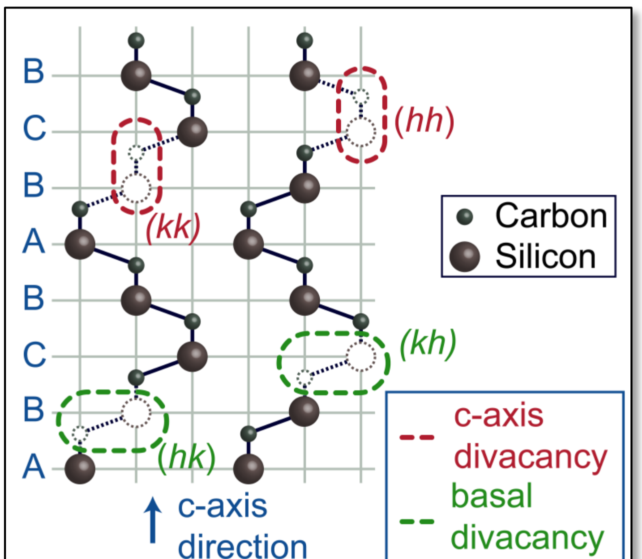


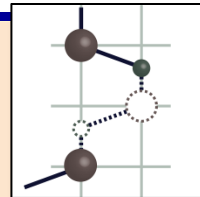
# Discovery of Spin Qubits in SiC

D. D. Awschalom, University of California – Santa Barbara

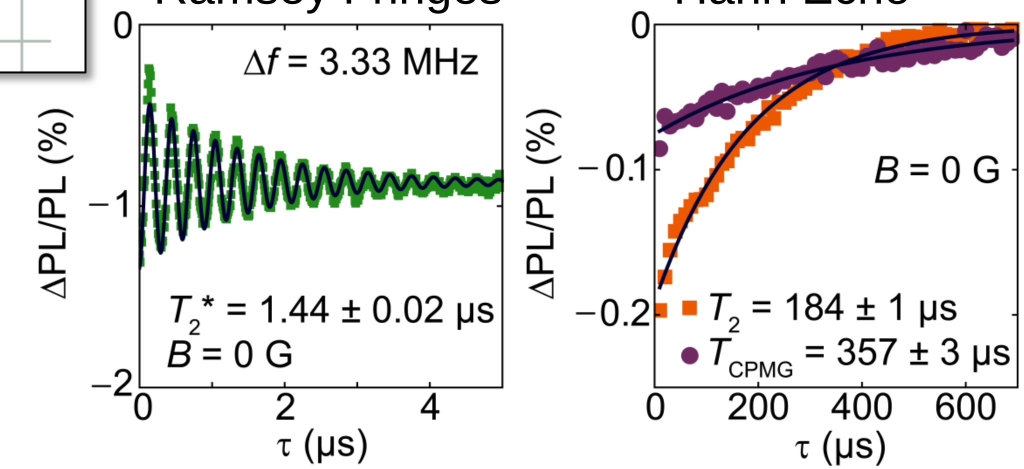
Based on existing technology:
- commercial wafers
- GHz quantum control
- room temperature
- telecom wavelengths
- robust $T_2$ ~ 300 μs

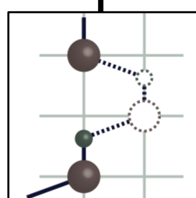
Different divacancy defect orientations



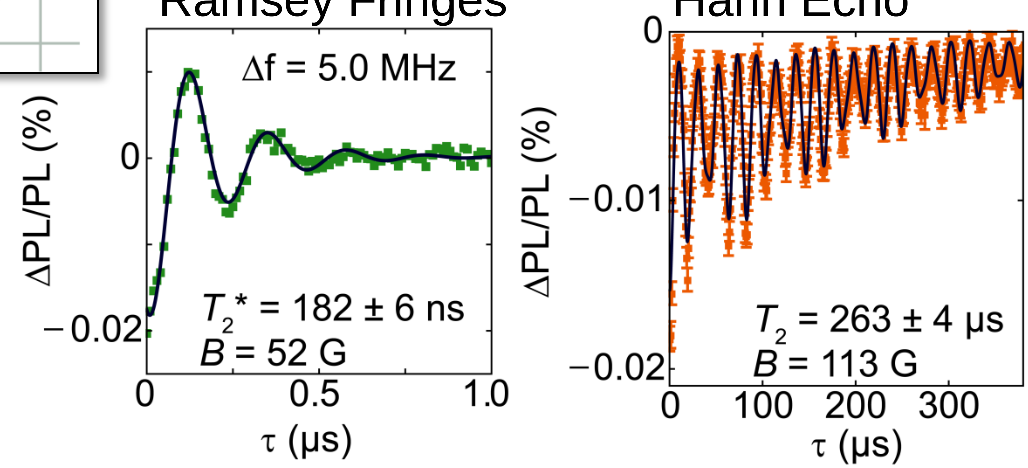



## Basal divacancy orientation



## C-axis divacancy orientation

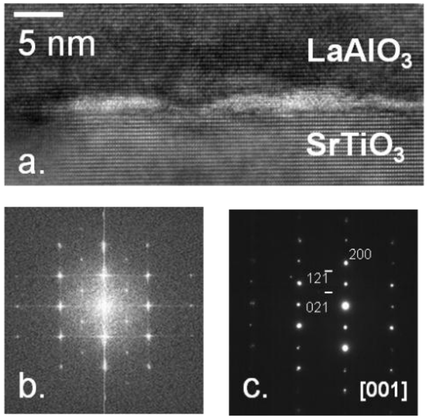


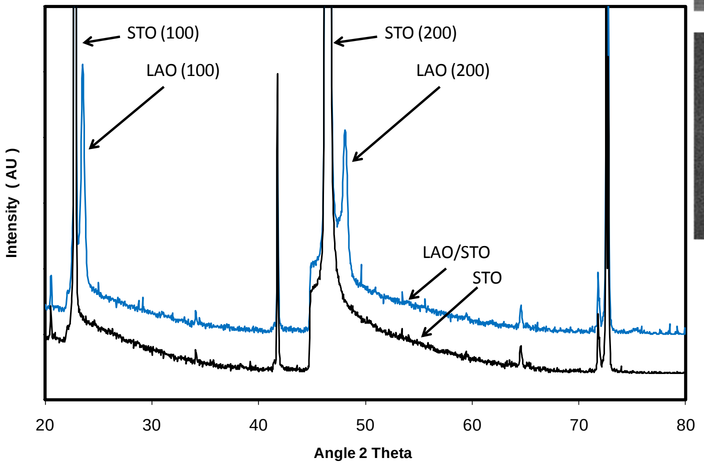

*Nature* **479**, 84 (2011)

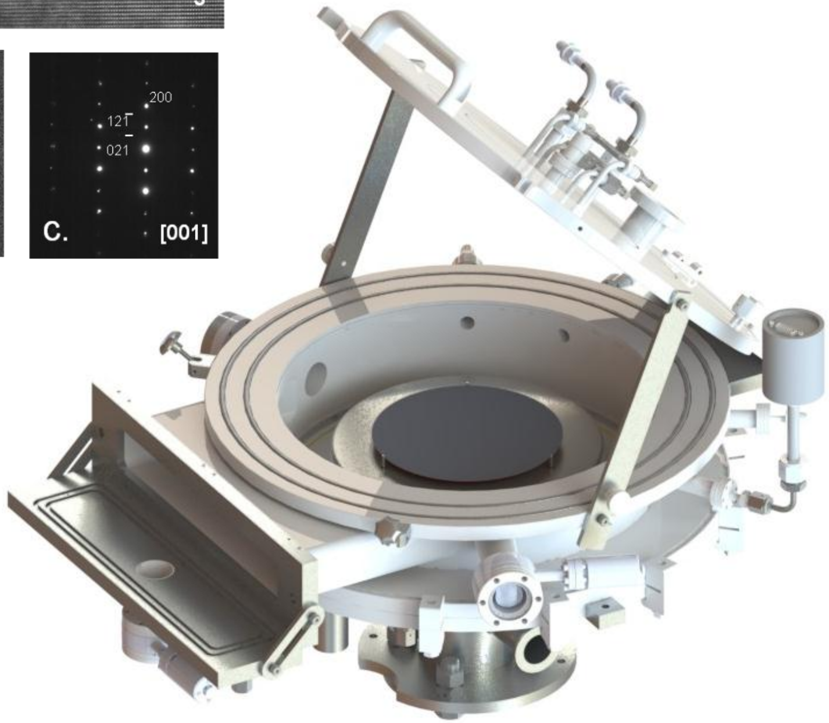
# Fab. for Oxide Film Hetero Devices

## STTR Phase II

Structured Materials Industries: Nick Sbrockey, Gary Tompa
Drexel University: Jonathan Spanier



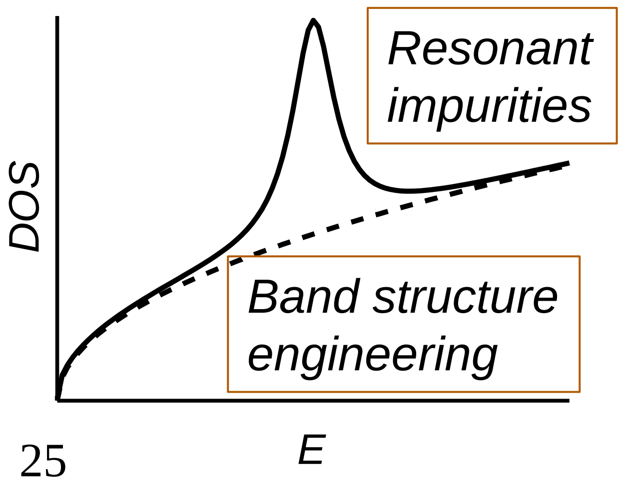
SMI and Drexel University have developed an atomic layer deposition (ALD) process for epitaxial $LaAlO_3$ films on $SrTiO_3$ substrates. XRD and TEM verify epitaxy. Electrical characterization shows conductivity, similar to $LaAlO_3$ / $SrTiO_3$ heterojunctions prepared by pulsed laser deposition (PLD).

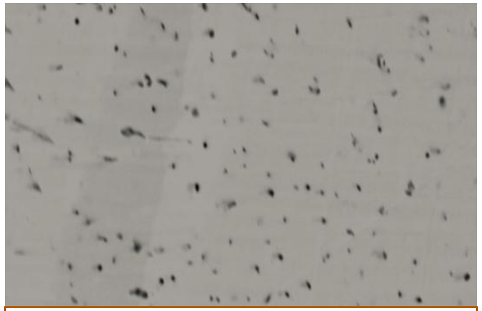
Recent work focused on scaling-up process technology & hardware to large wafer sizes & high volume production tools.

# CRYOGENIC PELTIER COOLING – FY10 MURI
## J. P. Heremans, Ohio State U.

- **Goal**: develop science to enhance thermoelectric performance of solid-state coolers in the **150 K – 10 K** range (cooling of IR, XR and $\gamma$-ray sensors); need **$zT > 1$-$1.5$**
- **Approach**
  - Two scientific tools
    - **(1) band engineering to enhance thermopower**
    - **(2) nanostructuring to decrease lattice thermal conductivity**
  - Four material systems
    - **(1) $Bi_{1-x}Sb_x$**
    - **(2) Tetradymites $Bi_2Te_3$-like**
    - **(3) sp/d hybridized semiconductors $FeSb_2$-like**
    - **(4) sp/f hybridized metals $CePd_3$-like**

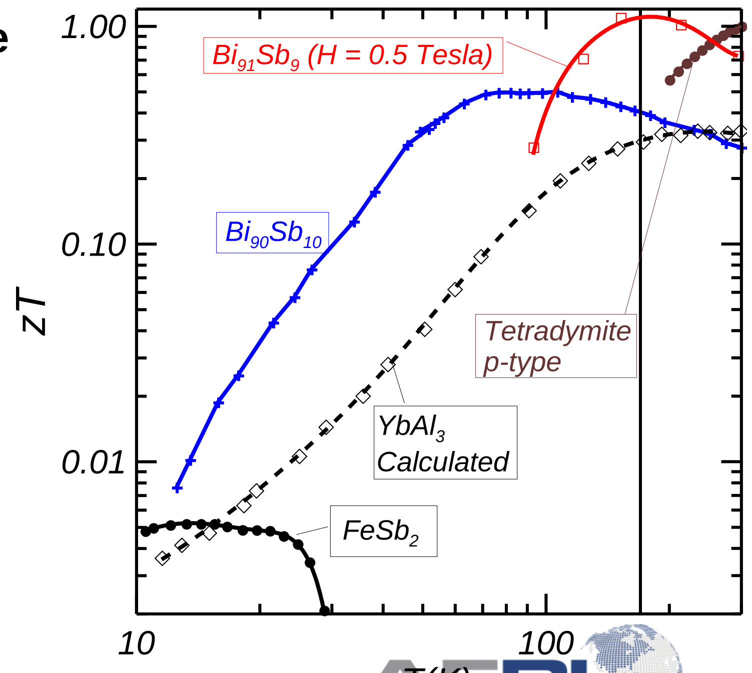
$$zT = \frac{S^2\sigma}{\kappa}T$$



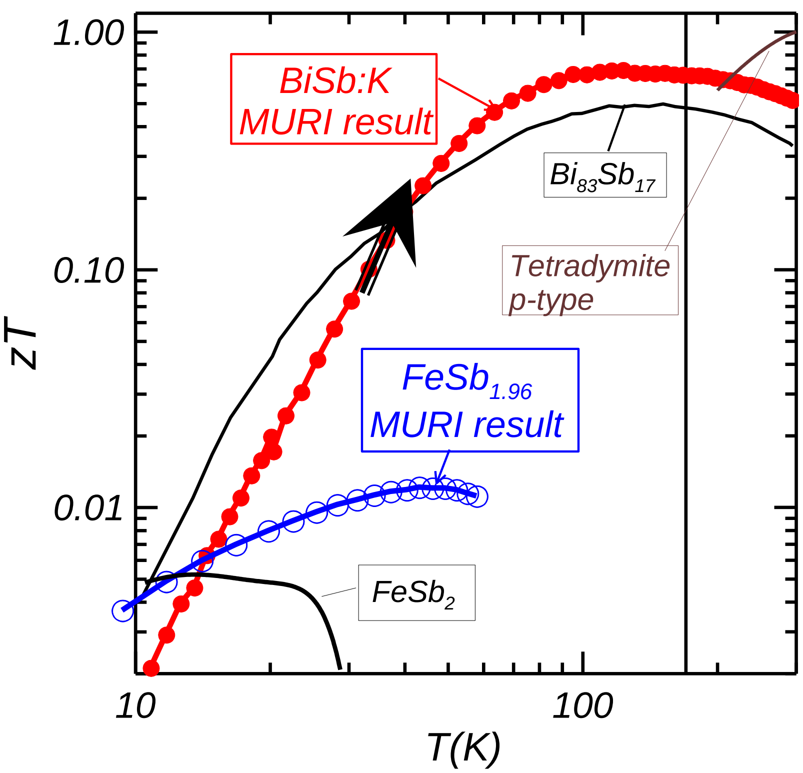
*nm-sized precipitates in BiSb-As reduce thermal conductivity*

**Starting point**



# CPC MURI Accomplishments Year 1

## J. Heremans, Ohio State U.




Overall progress:

- 40% increase in zT 50K <T < 300K in BiSb using K as resonant level
- 3x-increase in zT in $FeSb_2$ using nanostructuring

# Interactions with Other Agencies

| Agency/Group | POC | Scientific Area |
|---|---|---|
| ARO<br><br>ARL | Rich Hammond<br>Pani Varanasi<br>Paul Barnes | Metamaterials<br>Graphene<br>Superconductivity |
| DoE | Laura Greene, UIUC (EFRC)<br>Yvan Bozovic, BNL | Superconductivity<br>Superconductivity |
| ONR | Mark Spector<br>Chagaan Baatar | Metamaterials<br>Graphene |
| International | Taiwan<br>Korea<br>Israel<br>Netherlands<br>Brazil<br>Chile | Nanoscience<br>Nanoscience<br>Metamaterials, NS, SC<br>Superconductivity<br>Magnetic Materials, SC<br>Magnetic Materials |

# Thank you